Chapter 4
Level 2 Hypotheses

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4.1 Hypotheses

This section provides a pilot demonstration of different approaches to testing hypothesis L1.n (Table 5-1, page 5-4 of PATH Workshop 1 Information Package):

> Trends in stock indicators are related to trends in survival during the **xxx** stage;

where **xxx** can be freshwater spawning and rearing, juvenile migration, estuary and ocean residence, upstream passage, or prespawning survival. The stock indicators investigated in this chapter are spawner to recruit survival for 16 Columbia River spring chinook stocks, all spawning above Bonneville Dam.

The management implications of this set of hypotheses *may* be straight-forward: if stock indicators (e.g., spawning escapement, recruits/spawner) are closely related to trends in survival at one or more life stages, then management priorities should focus on those areas. However, stock-specific, life stage survival data for Columbia River chinook are very rare, confined mostly to downstream passage mortality and coded wire tag studies. Therefore, one must work with data on survival from adults in generation N to adults in generation N+1 — in this case, survival from estimated spawners to estimated recruits to the Columbia River mouth. While time-series data on these survivals can be shown, in many cases, to be associated with life-stage specific climatic and anthropogenic phenomena, it is usually impossible to test the hypothesis as stated above. Instead, one can test a related but rather different hypothesis, as follows:

> Trends in spawner to recruit survival are related to stressors during the **xxx** stage;

where **xxx** is defined as above. Three caveats therefore apply to the analyses and their management implications. First, absent additional life-stage survival studies, it is very difficult to say that environmental stressor **X** causes changes in life-stage survival **Y**. Second, even if a management action seems to affect a particular life stage (e.g., transportation and downstream survival or hatchery rearing and egg-to-parr survival), it may also have effects on subsequent phases in the population life cycle. Third, because the analysis is a regression approach using historical data, the usual disclaimer regarding association and causality applies. Finally, the relationships investigated are assumed to be log-linear(see Eq. 4.1).

Note that the analyses discussed in this section are closely related to the passage mortality analysis in Chapter 5. There are three major differences between this analysis and that of Chapter 5. First, the hypotheses cover *all* phases of the life cycle, not just downstream passage. The second difference follows from the first: because this analysis looks at all phases (spawning/rearing, downstream, ocean, and upstream survival) it employs a somewhat simpler suite of models, intended to be applied to a larger number of stocks. Third, where common effects are assumed for different stocks (e.g., ocean survival) they are assumed only for stocks in a relatively restricted geographic area. In contrast, the analysis in Chapter 5 assumes that all stocks have similar patterns of ocean survival.

4.2 Available Data

Data for spring chinook from the following areas are used in this analysis:

- John Day basin (Middle Fork, North Fork/Granite, and Upper Mainstem);
- Bear Valley/Elk Creek, Marsh Creek and Sulphur Creek in the Middle Fork of the Salmon;
- Minam and Imnaha basins;
- Wind and Klickitat, above Bonneville Dam but below other impoundments, and the Deschutes, above two dams;
- Entiat, Wenatchee, and Methow subbasin in the mid-Columbia;
- Poverty Flat and Johnson Creek spring/summer chinook in the South Fork of the Salmon River.

These are the same stocks used in Section 2. However, the focus here is on spawner-to-recruit survival, as opposed to the many other indices investigated in Section 2. ODFW, IDFG, and WDFW PATH participants have agreed to provide stock-recruit data for the Mackenzie, Umpqua, Hoh, Queets, Snake River fall chinook, Lewis, and Hanford reach. When these become available, they will be included in the final report.

As noted in the introduction, one must work with data on environmental conditions that may be correlated with salmon survival. This task is difficult, for three obvious reasons. The first is the lack of life-stage survival time series. This in turn means that any correlations or regression relationships that one might observe (say between an ocean index and rates of coded wire tag [CWT] recoveries) may not be caused by the ocean index but by some unobserved intervening variable. The second problem is that many environmental stressors have been identified as being important for some stocks at some time (see below for a few examples). A regression model that included all the potentially important variables (e.g., daily stream flows and temperatures, monthly ocean condition indices, etc.) would be hopelessly over-parameterized, and useless for making inferences about the linkages between environmental stressors and salmonid survival. Finally, even if one could use very detailed environmental data (e.g., using principal components and factor analysis to “compress” the information) such data — especially for freshwater spawning and rearing areas — are rarely available for long-term, consistently measured time periods.

For example, many stressors have been identified as potentially important for freshwater spawning and rearing.[1] These can be categorized into six broad areas:

1. In-stream temperature;
2. In-stream flow regime;
3. Channel morphology;
4. Food supply;
5. Stream substrate, including cobble embeddedness and percentage of fine sediment.
6. Habitat complexity, including in-stream structure and riparian vegetation.

Temperature, flows, and channel morphology are important for all freshwater life stages. Food supply is important for the rearing of fry to parr, while substrate is especially important for spawning and incubation.

[1] See, for example, Birch and Peters (no date), Bjornn 1984, Everest and Harr 1982, Hartman and Holtby 1982, Moring and Lantz 1975, Platts 1979, Reiser and Bjornn 1979, Rhodes at al. 1994, and Scrivener 1987 for overviews of potentially important relationships between land use and chinook or coho abundance.

These items cover some of the more important freshwater habitat variables that are often cited in the literature. However, models that relate management practices (e.g., irrigation diversions and screening, grazing, logging) to survival are still scarce.[2] An outstanding feature about most studies listed is the lack of controlled experimental approaches that can unambiguously relate changes in *habitat management* to changes in *fish survival* (the Carnation Creek and Alsea River studies, both done on coho, are notable exceptions). Instead, studies usually relate local habitat conditions to localized fish abundance. This sounds quite similar to the habitat management-fish survival problem, until one thinks the matter through (see below). Walters et al. (1989) point out some of the problems involved in detecting the effects of habitat changes on anadromous fish abundance, and propose a “staircase” experimental design to alleviate some of the difficulties. Indeed, these problems prompted Walters and Collie (1988) to ask the rhetorical question “Is research on environmental factors useful to fisheries management?” They point out that while studies have been moderately successful at predicting geographic *distributions* of fish, they do not do so well at predicting *recruitment* (i.e., survival rates). However, Walters and Collie (1988) are primarily concerned with stocks where the main management “control” is fishing effort. Columbia River stream-type, yearling migrant chinook (at least at the present time) have relatively low harvest rates.[3] As such, management of migratory, spawning and rearing habitat is arguably more important for these fish than for heavily exploited stocks. Nonetheless, their point is important: there are few convincing studies that demonstrate a relationship between survival rates and habitat conditions.

A number of streams have received extensive attention to one or more aspects of instream habitat. Studies by McIntosh (1993) and McIntosh et al. (1994a, 1994b) of changes in large pools in Eastern Oregon and Washington, and by Wissmar et al. (1994a, 1994b) in the mid-Columbia are two examples of long-term changes in channel morphology and land use practices. Platts et al. (1989) have studied changes in sediment delivery and accumulation in the South Fork of the Salmon River, and Lee at al. (1993), among others, have studied the effects of this sediment loading on fish survival. Data from these studies and others might be included in detailed analyses for stream where they apply, but they are not included in this analysis.[4]

Instead, this pilot analysis uses data that are available for a large number of stocks in the Northwest. Specifically, the information used for the pilot includes:

1. Annual monthly upwelling index at 48 degrees, just north of the mouth of the Columbia, during May in the year of out-migration.
2. An annual index of the strength of the Aleutian Low, the North Pacific Index, averaged over each winter. This is used for each winter when the fish are at sea.
3. Annual migration corridor flows in the year of out-migration (i.e., Snake and Columbia monthly average mainstem flows, averaged over April-June).
4. Annual minimum monthly average spawning/rearing area flows during the summer when the smolts are rearing from fry to parr, the year before out-migration.

[2] See, for example, Baker et al. 1995, Bisson and Sedell 1984, Bradford 1994, Carlson et al. 1990, Chapman and Knudsen 1980, Hartman et al. 1984, Kope and Botsford 1990, Murphy and Hall 1981, Platts and Nelson 1988, Platts et al. 1989, Sedell 1984, and Wissmar et al. 1994a and Wissmar et al. 1994b.

[3] Note that this does not apply to fall chinook, as opposed to the spring chinook included in this analysis.

[4] Note that detailed data could be used for the few stocks where it is available. The focus here is on data that can be used for many stocks in the Columbia, coastal Oregon and Washington, and California. Appendix 2.1 contains a general description of data in hand or which we expect to have for most of these stocks.

5. The number of dams in the year of out-migration in the migratory corridor.
6. The annual maximum monthly winter snow water equivalent in spawning and rearing areas, in the winter before out-migration.
7. Drought index in the summer of rearing from fry to parr.
8. Minimum monthly summer precipitation in the summer of rearing from fry to parr.

Data for each stock are shown in **Table 4.1**. See **Figure 4.1** below for an illustration of how these are thought to affect the stocks at each stage of the life cycle, and **Appendix 4.1** for tables of correlations among the variables for each subbasin. **Appendix 2.1** contains details on sources and definitions for the independent variables. For each stock, the years were chosen based on the availability of spawning escapement, recruitment, and the independent variables just noted.

Several potentially important stressors are missing from the list above. For example, logging, road construction, and grazing are often mentioned as potentially deleterious factors in spawning and rearing success (see for example Chapter 10 of this report). However, we have not yet been successful in obtaining data on these and other anthropogenic disturbances. We plan to address this in the next phase of the work. This leaves the number of dams as the only uniquely human-caused independent variable in the regression models, with migration and rearing area flows as (potentially) human-influenced. This may result in overstating the effects of dams and flows to the extent that they occur contemporaneously with other anthropogenic stressors.

Life Stage	**Independent Variable(s)**
Year of Subbasin Rearing from fry to parr	Parent Spawning Escapement, Snowpack, Spawning/Rearing Flows, Drought Index, Minimum Summer Precipitation During Year of Subbasin Rearing
Downstream Migration of Smolts	Number of Mainstem Dams in Migratory Corridor, Spring Flows in Migratory Corridor, Year of Downstream Migration
First Months in Ocean	May Upwelling Index, Year of Downstream Migration
Years of Ocean Residence	North Pacific Index (NPI) in 1st Through 3rd Year of Ocean Residence

Figure 4.1: Presumed linkage between independent variables and salmon life stages.

Note that only a subset of the variables was employed for any given stock (or group of stocks) and model. The number of dams could not be used for the Wind, Klickitat, and Deschutes, since this number did not change during the time when stock-recruit data are available. In addition, two classes of model were employed for most subbasins: one using snowpack and rearing area flows, and a second using the drought index and minimum summer precipitation. The latter pair of variables was available for more stocks and for a greater number of years than the former. If the analysis is extended to more stocks, the drought and precipitation indices may prove useful for analyzing the additional stocks.

It is obvious much research judgment was involved in the selection of these variables. Whenever one sees a study where the researcher had a wide variety of variables at their disposal and reports on only a small subset of them, one should be skeptical of the reported results. However, the selection of independent variables in this case is not as arbitrary as it might appear, for several reasons. First, the selection of variables did not depend on regression results. With one minor exception, these variables were the only ones used in the analysis. [5] Second, the annual time-step for the variables is determined by the nature of the dependent variables available — annual spawning escapement and recruitment to the Columbia. If additional independent variables are used in future, they will need to be converted to annual moments of some kind (means, minima, maxima, etc.). Third, the nature of the hypotheses under examination strongly suggests that data from most or all phases of the life cycle —spawning and rearing, downstream, ocean, and upstream survival– should be included in a model, if this is feasible.[6]

That having been said, however, the variables are one of a very large set of reasonable candidates that could be employed. The ocean indices (upwelling and NPI) were chosen primarily because they were both up-to-date and readily available, not because they were known to be closely related to salmonid ocean survival rates.[7] The reason for choosing average May upwelling (measured at 48 degrees N, 125 degrees W) was that this is when the stream-type chinook migrate seaward, but other months or stations (e.g., 45 degrees N) could have been used separately or in combination. Ocean temperature, sea-level height, and other ocean indices could have been used as well, although work by Chris Toole (personal communication, March 1996) suggests that these are strongly correlated with one another. Dan Bouillon has suggested using the Aleutian Low Pressure index (ALPI) instead of the NPI, but it is not yet available after 1989. The freshwater data used (spring migratory corridor flows, minimum average rearing area flows, and maximum winter snowpack) are subject to similar concerns. However, the range of potential indices available are not so large as for the marine environment, due to very limited data available for the 2-3 decade period of spawning/recruit data. Two obvious examples for the downstream migration corridor would be to use passage model back-casts of survival or water travel time instead of the number of dams and flow.

4.2.1 Recruitment Estimates

In reviews of the earlier draft there were several comments expressing concern about potential lack of independence among recruitment estimates. Petrosky at al. (1995) contains information on how these are calculated. However, it is worth giving a short summary of the spawner and recruit estimation methods, since these are quite different from those used in the Fraser River and elsewhere. The details vary somewhat among streams and years, but the same general method is used for most stocks in this analysis.[8] See Beamesderfer et al (forthcoming revision of Petrosky et al) for more details.

Each year, state and tribal biologists perform peak counts of the number of redds in an index area. These numbers are expanded to account for redds outside an index area, based on occasional surveys that encompass the entire known spawning area for each stock. The expanded redd counts are then extrapolated to estimated spawners based on assumptions about sex ratios. Comparisons of redd counts and weir counts for the Lemhi (see Chapter 5) suggest that the expanded counts are reasonably accurate. Spawners may include hatchery strays for some stocks and years.

In addition to counting redds, biologists also estimate the age structure of the spawning population based on scale samples and/or sizes of carcasses for a subset of each spawning population. This information is used

[5] The exception is that in addition to the number of dams in the migration path, I also tried to include the total length of reservoirs traversed by each stock in each year. The total length was perfectly collinear with the number of dams, however.

[6] Note that because recruitment is defined as recruitment to the mouth of the Columbia, we can get away without including variables related to upstream survival.

[7] Although there are several examples of studies of salmonid harvest and ocean indices (e.g., Beamish and Bouillon, 1993), I have found almost no studies of chinook escapement or recruitment in the literature.

[8] The exception is the Wind, which relies on peak counts of carcasses and live fish (Olaf Langness, Personal communication, June, 1996).

to estimate the number of recruits *to the spawning ground*. For most stocks, recruits are observed at ages 3-5. For example, if in 1980 200 spawners were estimated to be present, and if 1983's spawning count had 50 age-3 fish, 1984's 100 age-4 fish, and 1985's 150 age-5 fish, the spawning ground recruitment for the 1980 brood year would be (50+100+150) = 300. If age structure data are missing for some years and stocks, it is inferred or averaged from other years and/or closely related stocks for the same year.[9] Mini-jacks (age 2) are ignored in the reconstruction process.

Finally, the spawning ground recruits are expanded to recruits to the mouth of the Columbia by accounting for pre-spawning survival, subbasin harvest, losses between dams (i.e., fish that appear at a lower dam but are "lost" before the next dam upstream), and mainstem Columbia and Snake River harvest. The adjustment is done separately for each year, with differing harvest and interdam loss rates for spring and summer chinook. Subbasin harvest rates are estimated separately for each stock and year. Recruitment is corrected for hatchery strays, so that only progeny of the previous generations' naturally-spawning fish are counted as recuits.

Three items about this are relevant to the question of independence of recruitment estimates. First, the spawning ground recruitment data for each stock are independent of one another, except insofar as age structure data is "shared" among stocks due to missing information on individual stocks and years. Second, the Columbia River mouth recruitment figures are related to one another, in that groups of fish of the same age and stock (spring or summer chinook) passing the same point in the same year are assumed to have the same harvest and conversion rates. Third, the total recruitment and recruit-at-age information, while correlated, is derived from spawning ground escapement figures for different years for each stock and brood year.

One way to approach the question might be to think of it in the following terms. Assume that the spawning ground recruit data really is independent — that they are time series of independent random numbers. This seems reasonable, based on the information outlined above. Similarly, the information on age structure appears to be independently derived for each stock and brood year, except when missing data are filled in from other stocks or years. Next, assume that the conversion factors for harvest and interdam loss are derived independently, since they come from aggregate harvest compilations and dam counts.[10] Then, recruits to the Columbia can be viewed as the product of independent random variables: the spawning ground recruit estimates, age fractions for each group of spawning ground recruits, and the conversion factors. Looked at in this way, it would seem that the recruit number used in this analysis are indeed independent of one another. However, this is not to say that the estimates are uncorrelated, only that they are independently derived.

Obviously, what is required is a systematic investigation of the problem, based on CWT studies and the recruitment estimates already in hand. We plan to investigate this further in the future.

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[9] For all stocks outside the mid-Columbia, the spawning ages were estimated to be 3-5 years. For some mid-Columbia stocks, ages were estimated to be 3-6, with the 6-year age class being 0-2 percent of total recruits. We combined the 5 and 6 year olds into a single age-5 recruit class.

[10] This is not true in all cases, since some "turnoff" numbers for fish that turn off and spawn between dams are in fact derived from redd count information. This is the exception rather than the rule, however. Also, for the Imnaha, the conversion factors are an average of spring chinook and summer chinook conversion rates.

4.3 Analytical Methods

The general model under consideration is of the form shown below:

$$SV_n = f(S_{t-n}, Stressors_t, \ldots Stressors_{t-n}) . \qquad \text{Eq. 4.1}$$

where SV_n = survival rate of age n recruits, S_{t-n} is spawning abundance in the parent generation of age n recruits, and $Stressors_t$ are environmental stressors that may affect survival at different ages. Because of the geographic scope of the analysis, we want to devise a model that can be applied to a fairly large number of stocks across Washington, Oregon, and Idaho. This suggests models with a simpler structure than those used in Chapter 5, albeit using somewhat less sophisticated analytical methods. All models were estimated with SAS Proc GENMOD.

4.3.1 Single Stock, Pooled Age Classes

Petrosky et al. (1995) developed data on estimated spawner abundance (see Section 4.2.1) and recruitment to the Columbia River mouth for the stocks listed. During the run reconstruction, they also estimated the age structure of each population, using annual data on spawner ages where available and averages for years where annual data were not available.[11] This, in turn, means that the recruitment can be broken down into age classes, if one is willing to make similar assumptions for recruits (as opposed to spawners). Following Petrosky at al, I assumed that the age structure of recruits could indeed be inferred from the age structure of each year's spawning population for each stock.

Equation 4.2 shows the model estimated with pooled recruits:

$$Ln\Big((R_t + R_{t-1} + R_{t-2}) / S_{t-5}\Big) = b_0 + b_1 S_{t-5} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} +$$
$$b_4 MIGFLOW_{t-3} + b_5 SPFLOW_{t-4} + b_6 SNOW_{t-4} + b_7 NPI_{t-2} + b_8 NPI_{t-1} + b_9 NPI_t + e_t$$

Eq. 4.2

Where: R_t is recruits in year t,
S_{t-5} is parent spawning abundance,
$DAMS_{t-3}$ is the number of dams at the time the recruits out-migrated,
$MIGFLOW_{t-3}$ is mainstem flow during the outmigration period,
$SPFLOW_{t-4}$ is minimum summer monthly average flow during the year preceding outmigration,
$SNOW_{t-4}$ is maximum snowpack during the winter preceding outmigration,
NPI_{t-2} is the North Pacific Index in the recruits first ocean winter,
NPI_{t-1} is the North Pacific Index in the recruits second ocean winter,
NPI_t is the North Pacific Index in the recruits third ocean winter,
β_n s are the regression parameters to be estimated, and
ε_t is the regression error term, assumed to be distributed $N(0, \sigma)$.

[11] See Petrosky at al. (1995) for details on age estimation. Depending on the stock and year, this was either done through size-at-age relationships or scale analysis.

Note that since recruits may return at ages 3-5, not all fish will be subjected to ocean conditions in the second and third ocean winters. Finally, to facilitate comparisons across stocks, the variables were standardized to mean 0, unit variance.[12]

Obviously, this is simply an extended version of a linearized Ricker model. It makes the assumptions (among others) that the natural log of survival rate is linearly related to the transformed environmental variables, and that error terms are "nice," neither of which may be true. These are obviously strong assumptions, but they seem to be a reasonable starting point.

Substituting the precipitation and drought indices for tributary flows and snowpack gives:

$$Ln\left((R_t + R_{t-1} + R_{t-2}) / S_{t-5}\right) = b_0 + b_1 S_{t-5} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} + b_4 MIGFLOW_{t-3} + b_5 PRECIP_{t-4} + b_6 DROUGHT_{t-4} + b_7 NPI_{t-2} + b_8 NPI_{t-1} + b_9 NPI_t + e_t$$

Eq. 4.3

Equation 4.3 is identical to 4.2, except that minimum summer precipitation (*PRECIP*) and the summer drought index (*DROUGHT*) are substituted for spawning/rearing area flow and snowpack, respectively. Note that Equations 4.2 and 4.3 assume that the NPI in the second and third ocean years affect all age classes, even though some fish will already have returned to freshwater to spawn.

4.3.2 Single Stock, Multiple Age Classes

The model in Equations 4.2 and 4.3 can readily be extended to take advantage of the age-class structure of recruitment. Instead of estimating one regression model per stock, one can instead estimate one per age class:

$$Ln\left(R_{t-5+n} / S_{t-5}\right) = b_0 + b_1 S_{t-5} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} + b_4 MIGFLOW_{t-3} + b_5 SPFLOW_{t-4} + b_6 SNOW_{t-4} + \sum_{i=3}^{n} b_{7+i-3} NPI_{i-n+2} + e_{n,t}$$ Eq. 4.4.

$$Ln\left(R_{t-5+n} / S_{t-5}\right) = b_0 + b_1 S_{t-5} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} + b_4 MIGFLOW_{t-3} + b_5 PRECIP_{t-4} + b_6 DROUGHT_{t-4} + \sum_{i=3}^{n} b_{7+i-2} NPI_{i-n+2} + e_{n,t}$$ Eq. 4.5.

Where n is the age (3 to 5) of each group of fish at recruitment to the Columbia, and other terms are as defined for Eq. 4.2 and 4.3. The summation term simply accounts for the fact that the exposure to winter

[12] Note that for the single-stock, single (or pooled) age class models, the R/S and spawner data were not standardized.

ocean conditions depends on the age at recruitment to the river mouth: age 3 recruits spend only one winter at sea, while age 5 recruits spend three winters in the ocean.

Under the assumption that all recruits (regardless of age) are exposed to the same environmental stressors and react to them the same way (with the exception of the NPI) one imposes equality constraints on β_1 through $ß_6$ for the three equations (one per age class), and on the NPI's that each age class has in common (e.g., all age classes are at sea at age 3, while only 4 and 5 year olds are at sea at age 4). For example, for any given stock, $ß_1$ for age 3 recruits must equal $ß_1$ for the age-4 and $ß_1$ for age-5 recruits.[13] The result is, of course, a General Linear Model (GLIM) extension of Equations. 4.2 and 4.3, which accounts for the extra subscript on the error term. The constraints account for the rather awkward character of the lags in the model.

4.3.3 Multiple Stocks, Pooled Age Classes

Equations 4.2 and 4.3 can also be extended to the case where several stocks share the same conditions outside the subbasin:

$$Ln\left(R_{t,i} + R_{t-1,i} + R_{t-2,i} / S_{t-5,i}\right) = b_{0,i} + b_{1,i}S_{t-5,i} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} + b_4 MIGFLOW_{t-3} + b_{5,i} SPFLOW_{t-4,i} + b_{6,i} SNOW_{t-4,i} + b_7 NPI_{t+2} + b_8 NPI_{t+1} + b_9 NPI_t + e_{t,i} \quad \text{Eq. 4.6}$$

$$Ln\left(R_{t,i} + R_{t-1,i} + R_{t-2,i} / S_{t-5,i}\right) = b_{0,i} + b_{1,i}S_{t-5,i} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} + b_4 MIGFLOW_{t-3} + b_{5,i} PRECIP_{t-4,i} + b_{6,i} DROUGHT_{t-4,i} + b_7 NPI_{t+2} + b_8 NPI_{t+1} + b_9 NPI_t + e_{t,i} \quad \text{Eq. 4.7}$$

Equations 4.6 and 4.7 are multi-stock versions of 4.2 and 4.3, with the subscript i to denote the stock.. Conditions the fish meet outside the subbasin are assumed to prompt identical responses by each stock, while within-subbasin conditions are assumed to differ by stock.

4.3.4 Multiple Stocks, Multiple Age Classes

The models in Equations 4.6 and 4.7 can be extended to multiple stocks and multiple age classes. The key to doing so is to assume that all stocks from, say, the Salmon *or* John Day have the same exposure and response to downstream and ocean conditions. This is essentially a GLIM analog of the methods used in Chapter 5. The equations to be estimated are as follows:

$$Ln\left(R_{t-5+n,i} / S_{t-5,i}\right) = b_{0,i} + b_{1,i}S_{t-5,i} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} + b_4 MIGFLOW_{t-3} + b_{5,i} SPFLOW_{t-4,i} + b_{6,i} SNOW_{t-4,i} + \sum_{j=3}^{n} b_{7+j-3} NPI_{j-n+2} + e_{n,t,i} \quad \text{Eq. 4.8.}$$

$$Ln\left(R_{t-5+n,i} / S_{t-5,i}\right) = b_{0,i} + b_{1,i}S_{t-5,i} + b_2 DAMS_{t-3} + b_3 UPWELL_{t-3} +$$

[13] Note that the coefficients are simply constrained to equal each other, not to be equal to a constant.

$$b_4 \, MIGFLOW_{t-3} + b_{5,i} \, PRECIP_{t-4,i} + b_{6,i} \, DROUGHT_{t-4,i} + \sum_{j=3}^{n} b_{7+j-3} \, NPI_{j-n+2} + e_{n,t,i} \qquad \text{Eq. 4.9.}$$

The only difference between 4.4 and 4.8 is the subscript (to denote subbasin) on the ß's for the intercept (Ricker alpha), spawners (Ricker beta), spawning flow or precipitation and snowpack or drought index. Essentially, this says that stock productivity (the intercept) and carrying capacity ($ß_{1,i}$s) are different across stocks, and that "within-subbasin" environmental conditions affect different stocks in different ways. On the other hand, dams, out-migration flows, and ocean conditions are assumed to have the same effect on any given group of stocks. Note that this is an assumption that is very difficult to verify. For example, little information is available on within-season, downstream migration timing of individual wild stocks, which may well affect their downstream survival.

4.3.5 Expected Results

In comments on the earlier draft, reviewers suggested that we "predict" the effects of the environmental stressors prior to actually performing the analysis. The predicted effects, then, are as follows:

- Increased spawner abundance will result in lower survival.
- The NPI (which is negatively correlated with El Nino events) will have a positive relationship with LN (R/S).
- The upwelling index will have a positive relationship.
- Spawning/rearing area flows will have a positive relationship.
- Snowpack will have a positive relationship.
- The drought index (loosely defined as the excess of precipitation over evaporation) will have a positive relationship.
- Minimum summer precipitation will have a positive relationship.
- Dams will have a negative effect.
- Migration corridor flow will have a positive relationship.

As will be seen, some but not all of these hypotheses were confirmed by the empirical results.

4.3.7 A Note on Time Series Correlations

One reviewer of an earlier draft noted that intra-series correlation is likely to be a problem for the data used here, given that these correlations are apparent in the time series of spawning and escapement.[14] He was concerned that it may reduce the apparent number of degrees of freedom in the data, and hence reduce the significance of reported regression results. He also suggested the use of GLIM rather than Seemingly Unrelated Regression (SUR) techniques, which we have done here.

[14] Intra-series or autocorrelation means that a variable measured at time t may be correlated with the same variable measured at time t-1.

There are several possible ways to address the intra-series correlation problem. One is to use classical time-series regression techniques (ARIMA, etc.). Unfortunately, the usual rule of thumb is that the methods require at least 50 years of data to work well, and we have at most 30 or so years of spawning escapement information. A second possibility (as in Chapter 2) is to reduce the number of degrees of freedom based on low order autocorrelation. While effective for correlations, however, the method is not directly applicable to GLIM analyses. In principle, it should be possible to extend these methods to GLIM techniques, but we have not had sufficient time to do so. Finally, it is worth noting that the concerns about intra-series correlation apply directly to time-series data on abundance, and are less applicable to time-series data on survival (i.e., recruit/spawner ratios), which are the subject of this chapter's analysis.

To address this issue, we have chosen to concentrate on multi-stock, multiple age class models (see next section). This has the effect of greatly increasing the number of degrees of freedom, from the 10-20 using single-stock, single age class models to 100 or more degrees of freedom in the models estimated. It is to be hoped that the much larger effective number of observations, in combination with the concentration on R/S survival, will ease the intra-series correlation problem.

4.4 Results

4.4.1 Single Stock, Pooled Age Class

Single-stock pooled age class results are shown in **Table 4.2a** and **4.2b**. We discuss the models using the drought and precipitation indices first, followed by those using snowpack and spawning area flows.

Of 16 stocks, 13 show a positive and significant (at 0.05) intercept (the Ricker alpha), while 10 have a significant (and negative) coefficient for spawners (the Ricker beta)[15]. None show a negative intercept or a positive relationship with spawning escapement. The relationships found in the data are consistent with a density-dependent spawner-recruit relationship.

The effects of the NPI on survival are not so clear. All three John Day stocks show a positive relationship with the NPI in the 2nd ocean winter, as does one of the mid-Columbia stocks. Only one stock (in the John Day) shows a positive relationship with NPI in the last (third) ocean winter. The upwelling index shows a significant (and unexpectedly negative) relationship only in the Minam.

Migration corridor flows have a positive relationship with recruitment for all three mid-Columbia stocks, for the Minam, and Marsh Creek. They also have a negative relationship to one of the Lower Columbia stocks, which was not expected. However, this stock (the Wind) is an outlier in other respects, as well (see Chapter 2 for details).

The number of mainstem dams is negatively related to survival for 8 of the 13 stocks where its effects could be estimated. Recall that for the Deschutes, Klickitat, and Wind, the number of dams in the migratory corridor was constant throughout the period when spawner and recruit data are available.

The drought index had a positive coefficient for all three mid-Columbia stocks, as well as one Grande Ronde and one Snake River spring chinook stock.

[15] Unless otherwise noted, only coefficients significant at 0.05 or better will be designated as positive or negative in the discussion. Therefore "positive" should be read as "positive and significant at 0.05 or better," conversely for negative.

Minimum summer precipitation had a (surprisingly) negative relationship with three stocks. See the "Discussion" section for more details.

The results for the models using snowpack and tributary flows (**Table 4.2b**) are similar to those using the climatic indices regarding coefficients for the intercept, spawners, and dams[16]. However, no stock shows a relationship to upwelling, and only three (as opposed to four) stocks show a relationship with the NPI. Three stocks show a positive relationship with snowpack, and two show a positive relationship with tributary flows. The modest differences for the two classes of spawning and rearing condition variables suggests that there may be some correlation between the independent variables. Correlation tables for each subbasin are shown in **Appendix 4.1**.

The results from the single-stock, single age class models should be viewed with some skepticism. The models estimated contain ten coefficients and 20-30 observations, making it likely that they are over-parameterized. In addition, they do not take advantage of two plausible assumptions:

1. Recruits from the same brood year but returning at different ages at return respond similarly to common environmental stressors.
2. Fish from nearby streams but having similar migration timing will respond similarly to common environmental stressors.

If one is comfortable with these assumptions, then the number of observations can be increased by ten-fold or more. The next sections discuss the results from multiple age class and multiple stock models.

4.4.2 Single Stock, Multiple Age Classes

Single stock, multiple age class results are shown in **Table 4.3a and Table 4.3b**. We discuss the models using the drought and precipitation indices first, followed by those using snowpack and spawning area flow.

As with the single age class models, 12 of 16 stocks have a negative coefficient for spawner abundance.

Four stocks showed a positive relationship with the NPI in the last ocean winter. One stock showed a positive relationship with the NPI in the second ocean winter, and one (Poverty Flat) a negative relationship. Two mid-Columbia stocks showed a positive relationship with the NPI in the first ocean winter, while Marsh Creek had a unexpected negative relationship.

Four downstream stocks showed a negative relationship to the upwelling index, while one upstream stock (Sulphur Creek) had a positive relationship.

Nine stocks showed a positive relationship with migration corridor flow, and 10 had a negative relationship with the number of dams.

Of five stocks showing a relationship with the drought index, all were positive, as expected. Only one stock (Klickitat) showed a significant (and negative) relationship to the minimum precipitation index.

[16] Note that the snowpack/tributary flow models could not be estimated for the lower Columbia stocks due to missing data for several years. See Table 4.1 for details.

Of 13 stocks included in the snowpack/tributary flow models (**Table 4.3b**), 11 had a negative relationship with spawner abundance.

Only one (John Day North Fork) had a significant coefficient for the NPI in the last ocean year. John Day Middle Fork had a positive coefficient for the NPI in the second ocean winter, while Marsh Creek and Poverty Flat both had negative coefficients. All three mid-Columbia stocks had positive coefficients for the NPI in the first ocean winter. Two of the three John Day stocks had negative coefficients on upwelling.

Ten stocks showed a positive relationship with migration corridor flow, and had a negative relationship with the number of dams.

Snowpack was positively related to survival for three stocks scattered through the mid-Columbia and Snake, while two mid-Columbia stocks had a positive relationship between survival and spawning/rearing area flows.

4.4.3 Multiple Stocks, Single Age Class

Multiple-stock, single age class results are shown in **Table 4.4a and 4.4b**.

The stocks have been combined as follows:

Lower Columbia:	Deschutes, Wind, and Klickitat
John Day:	Middle Fork, North Fork/Granite, and Upper Mainstem
Mid-Columbia:	Entiat, Wenatchee, and Methow
Grand Ronde + Snake Springs:	Imnaha, Minam, Bear Valley/Elk, Marsh, and Sulphur
Snake Summers:	Johnson Creek and Poverty Flat

We discuss the models using the drought and precipitation indices first, followed by those using snowpack and spawning area flow.

Of the five stock groupings, all but the Snake summers have significant, negative coefficients on spawners, suggesting a density-dependent effect. The John Day aggregate has positive coefficients for the 2nd and 3rd ocean year NPI, while the mid-Columbia has positive coefficients for the 1st and 2nd ocean winter.

The Lower Columbia aggregate is the only group to have a significant coefficient on upwelling.

The John Day, mid-Columbia, and Grande Ronde/Snake Spring aggregates all have positive coefficients on migration corridor flow, while the mid-Columbia and both Snake aggregates have negative coefficients on the number of migratory corridor dams.

The drought index has a positive relationship to survival for the mid-Columbia and Grand Ronde/Snake spring aggregates. The precipitation index has a significant (negative) relationship only with the Grand Ronde/Snake aggregate.

For the snowpack/tributary flow models, the spawner and dam coefficients show the same patterns as for the drought/precipitation index models. Migration corridor flows are no longer significant for the John Day.

The John Day aggregate again has positive coefficients for the 2nd and 3rd ocean year NPI, while the mid-Columbia no longer has a significant relationship to the NPI.

Neither snowpack nor tributary flows have significant relationships to survival for these models.

4.4.4 Multiple Stocks, Multiple Age Class

Multiple-stock, multiple age class results are shown in **Table 4.5a and 4.5b**. We discuss the models using the drought and precipitation indices first, followed by those using snowpack and spawning area flow.

Of the five stock groupings, all but the lower Columbia have significant, negative coefficients on spawners, suggesting a density-dependent effect.

The John Day aggregate has positive coefficients for the 2nd and 3rd ocean year NPI, while the mid-Columbia has positive coefficients for the 1st and 2nd ocean winter. The Grand Ronde/Snake spring aggregate has a negative coefficient on the NPI is the 2nd ocean winter.

The Lower Columbia, John Day, and Snake summers all have a negative coefficient on upwelling.

The John Day, mid-Columbia, and Grande Ronde/Snake Spring aggregates all have positive coefficients on migration corridor flow, while the mid-Columbia and both Snake aggregates have negative coefficients on the number of migratory corridor dams.

The drought index has a positive relationship to survival for the mid-Columbia and Grand Ronde/Snake spring aggregates. The precipitation index has a significant (negative) relationship with the Grand Ronde/Snake aggregate, but is positive for the mid-Columbia.

For the snowpack/tributary flow models, the spawner coefficients show patterns similar to the drought/precipitation index models, but spawners are no longer significant for the John Day.

The John Day aggregate again has positive coefficients for the 2nd and 3rd ocean year NPI, while the mid-Columbia no longer a significant relationship to the NPI in the 2nd year, though the 1st is still positive. The Grand Ronde/Snake aggregate has an unexpected negative coefficient on the 2nd winter NPI. Upwelling is significant only for the John Day.

Migration corridor flow coefficients are positive for all stocks except the Snake summers, while dams are negative for all stocks.

Snowpack has positive coefficients for the mid-Columbia and Grand Ronde/Snake spring composite. Subbasin flows are significant only for the mid-Columbia.

4.5 Discussion and Research Implications

As noted earlier, some caution is needed in interpreting the results. Regardless of the specific model employed, the basic survival data is based on estimates of spawning abundance and recruits to the mouth of the Columbia. These regression techniques can provide information about the association of life-stage specific stressors and spawner-to-recruit survival. However, they cannot provide cause-and-effect evidence of the type derived from controlled experiments. Neither can they provide data on survival at particular life stages, given the nature of the dependent variable. Finally, the only unambiguous anthropogenic variable included is the number of dams in the migratory corridor. Other information on land use and other habitat alterations has not been gathered for most stocks.[17]

Given these caveats, however, the results do contain some interesting patterns, as shown in **Table 4.6**. The table is arranged with aggregate stocks (Lower Columbia, etc.) in the columns, and a summary of the significant results in the body of the table. For example, the John Day (in aggregate) has 24 estimates of the NPI in the 3rd ocean winter: 3 stocks * 4 types of model * 2 types of subbasin-specific variables (drought/precipitation vs. snowpack and tributary flows). Of the 24 results for the NPI in the 3rd ocean winter, none were significant and negative, and 17 were significant and positive. This is simply a compact way of summarizing the results from **Tables 4.2a** through **4.5b.** The intent is to give the reader some idea of the contrasting results for different stocks and stressors. Is assessing this, one should be aware of the large number of estimates, and the corresponding fact that some could be expected to differ from zero by chance. In the example noted, 24*0.05 =1 significant result might be expected from chance alone.

Increased spawning escapement had a negative effect on survival for most stocks, ranging from 90% of the models estimated for the Grand Ronde/Snake River spring aggregate to 63% of the results for the Snake summer chinook. This is consistent with density dependence playing a role in survival. However, we made no attempt to assess the applicability of a Ricker model as opposed to a Beverton-Holt or other density-dependent model.

The NPI in the 3rd ocean year was generally unrelated to survival, with the John Day aggregate being a strong exception, at 71% of the models estimated having a positive relationship. The NPI in the 2nd ocean year was positively related to survival for 79% of the John Day models and 33% of the mid-Columbia models. Interestingly, it was also negatively related to survival for 28% of the Grand Ronde/Snake River spring models. The 1st year NPI was usually unrelated to survival, but the mid-Columbia was an important exception, with 63% of the models estimated having a positive relationship. Within the limits of the regression approach, this is not what one would expect if variations in ocean survival are related mostly to the first ocean winter.

The upwelling index also showed a marked contrast among stocks, being negatively related to survival for 75% of the Lower Columbia models, 42% of the John Day results, and 13% of the Snake summer chinook models. It is also the only variable that show a “mix” of significant positive and negative results for the same stock, for the John Day (4% and 42%), and the Grand Ronde/Snake River spring aggregate (3% each). Note that the 3% results are well within what might be expected from chance alone. As with the NPI, the John Day is quite different from most of the other stocks. The negative relationship was not expected; see below for further discussion.

Migration corridor flow results are also a mixed bag. For the Lower Columbia, 8% of the results show an (unexpected) negative relationship with flow. The John Day has a positive relationship in over half the results, while the mid-Columbia and Grand Ronde/Snake River springs show positive effects for nearly all of the models. Interestingly, no significant flow effects were found for the Snake River summer chinook.

As might be expected, migration corridor dams have relatively little effect on the John Day, none on the lower Columbia (since it could not be estimated), and strong negative effects on all three up-river aggregates.

[17] Note that IDFG, ODFW, and WDFW have provided subjective rankings of spawning, rearing, and over-wintering habitat. However, because these rankings usually do not change over time, they were not included in this round of modeling.

The drought index and minimum precipitation index also have widely varying effects. The drought index is positively related to an amazing 100% of the mid-Columbia survival models, and 70% of the Grand Ronde/Snake River spring models. The minimum precipitation index is sometimes positively related (for the mid-Columbia) and more often negatively (unexpectedly) related to survival (for the Grand Ronde/Snake River spring, particularly).

Finally the snowpack and tributary flow have a positive relationship for roughly half of the mid-Columbia models and (for snowpack only) 45% of the Grand Ronde/Snake River spring models.

There are several research implications of these findings. First, because the stocks differ substantially in their responses to the NPI and the upwelling index, it suggests that more work should be done on their ocean distributions and ocean survival. In addition, it would be useful to add some additional ocean indices, such as the Aleutian Low Pressure Index (ALPI). Work on ocean distribution of coded wire tagged (CWT) hatchery spring chinook from lower Columbia hatcheries in the Wind, Deschutes and Klickitat suggests (based on modest numbers of ocean recoveries) that most of these stocks are recovered north of the Columbia (Paulsen and Fisher, 1996). In contrast, spring chinook from Snake River hatcheries are either not recovered in the ocean at all, or are found only south of the Columbia. If these distributions apply to naturally spawning fish (for which no CWT data exist) they may help explain the differing responses to ocean conditions. It also suggests that ocean condition indicators in areas where the respective CWT groups have been found should be used in place of the “generic” indices used here. In addition, these findings may also affect assumptions that underpin the analysis in Chapter 5. That work assumes that there is no systematic difference between Snake and lower river ocean survival that coincided with the construction of the Snake River dams.

The fact that increases in the May upwelling index are associated with decreases in survival for the John Day and lower river stocks is clearly cause for concern. Work on coho has suggested the opposite: that increased upwelling is associated with increased survival. The most likely explanation is that we have simply chosen the wrong upwelling index: that upwelling in a different month or perhaps a different indicator, such as the date of the spring transition, would have been a better indicator. Further work on this is a straight-forward extension of the present analysis.

The findings for dams and migration are very strong: in almost all cases, fish that should be affected by in-river migration conditions show significant effects. The exception to this rule is Snake summer chinook, which have no significant relationship with mainstem flows. A potential extension would be to add in other climatic indices in the winter and spring just before downstream migration, to try to separate effects of (proxies for) fish condition from those of migration stresses proper. Another would be to run the passage models for all 16 stocks and years (from 1960-1991) and use these back-casts in place of the dam and flow variables. This would give one some notion how well the passage models fit the data on spawner to recruit survival. It could also provide a check on how good the dam and flow indices are as proxies for downstream survival. Water travel time could also be used as a proxy, but it is likely to be confounded with the number of dams.

The models’ performance on spawning and rearing condition indices is more ambivalent. The drought index, spawning and rearing area flow index, and snowpack performed as expected, all having positive signs where they were significant. The precipitation index, on the other hand, was negative in many cases, which was not at all what had been expected. One possibility is that it may be correlated with other events (i.e., flooding) that are not evident in the data used. Alternatively, it may simply be a case of using the “wrong” variable. As with the upwelling index, further work in this area is any easy extension of this present analysis.

That having been said, however, there is a gaping hole in the data, and hence in the analysis: the near-total absence of information on anthropogenic alteration to spawning, rearing, estuarine, and upstream habitat and migration corridors. The consensus among many habitat researchers is that Columbia River habitat was severely damaged before the advent of systematic spawning ground surveys (see Chapter 10 and references cited earlier). However, grazing, logging, road construction, irrigation withdrawals, and other potentially deleterious activities continue in many subbasins. We have received almost no data in response to repeated requests to federal land management agencies for time-series data on these subjects. The result is that the only unambiguous human-caused stressor included is the number of dams, with flows being influenced by people as well. The possibilities for confounding with other stressors that may also increase over time is obvious.

Without additional information, it is impossible to assess the effects of recent land use practices on fish survival. This is obviously an important question for PATH. We strongly suspect that the data are in fact available, since they would be needed to calculate and collect fees for the use of federal lands. Acquiring the data will probably involve field trips to the relevant federal district offices to collect and collate the information.

Beyond refining the analysis for the 16 stocks already included, reviewers of earlier drafts recommended broadening the scope of the analysis to include other runs of chinook, steelhead, and stocks outside the Columbia. As noted earlier, state fishery agency personnel are working on run reconstructions for another 6-7 chinook stocks. These will be analyzed when the reconstructions are complete. In addition, Carl Walter's suggestion of using a simpler definition of recruits (see Chapter 2) would make it relatively easy to include perhaps 20-30 additional stocks in the analysis, since formal run reconstructions would not be required.

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Table 4.1: Regression model data.

Note: NPI: North Pacific Index
Note: Upwelling Index, May, Year of Downstream Migration
Note: April-June Avg. Migration Corridor Flow, Year of Downstream Migration
Note: # of Dams in Migration Corridor, Year of Downstream Migration
Note: Drought Index, Year of Subbasin Rearing
Note: Min. Precipitation, Year of Subbasin Rearing
Note: Max. Winter Snowpack, Winter/Spring in Year of Subbasin Rearing
Note: Min. Summer Spawning/Rearing Area Flow, Year of Subbasin Rearing

Table 4.2a: Single Stock, Single Age Class, Generic Environmental Variables.

Table 4.2b: 1 Stock, 1 Age Class, Specific Environmental Variables.

Table 4.3a: Single Stock, Multiple Age Classes, Generic Environmental Variables.

Table 4.3b: Single Stock, Multiple Age Classes, Specific Environmental Variables.

Table 4.4a: Multiple Stock, Single Age Class, Generic Environmental Variables.

Table 4.4b: Multiple Stocks, Single Age Class, Specific Environmental Variables.

Table 4.5a: Multiple Stock, Multiple Age Classes, Generic Environmental Variables.

Table 4.5b: Multiple Stock, Multiple Age Class, Specific Environmental Variables.

Table 4.6: Results Summary.

Chapter 4 Appendix 1

Table 4.1.1: Correlations among Regression Variables.

Note: NPI: North Pacific Index
Note: Upwelling Index, May, Year of Downstream Migration
Note: April-June Avg. Migration Corridor Flow, Year of Downstream Migration
Note: # of Dams in Migration Corridor, Year of Downstream Migration
Note: Drought Index, Year of Subbasin Rearing
Note: Min. Precipitation, Year of Subbasin Rearing
Note: Max. Winter Snowpack, Winter/Spring in Year of Subbasin Rearing
Note: Min. Summer Spawning/Rearing Area Flow, Year of Subbasin Rearing